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Hybrid floating breakwater-WEC system: A review

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Abstract:

Ocean wave energy is attractive for its large reserves, exploitability and low emissions. Although many Wave Energy Converter (WEC) concepts have been proposed, high construction cost hinders the engineering application of WECs. Similar challenges arise in the applications of floating breakwaters. The construction cost can be reduced by combining different structures as one integrated system which has the advantage of cost-sharing, space-sharing and multi-functionality. This integrated design approach has stimulated the rapid development of the hybrid system combining floating breakwaters and WECs in recent years. The novel floating breakwater-WEC system is often classified as a wave-energy-utilizing type floating breakwater. The different approaches for integrating floating breakwaters and WECs are summarized in this review. The hydrodynamic performance and power take-off performance of these hybrid floating breakwater-WEC systems are the focus of this review. The insights gained from previous studies of this system and the potential challenges for further developments of this technology are also provided. The cost-sharing and multi-function of the breakwater-WEC system can help facilitate the engineering application of the floating breakwaters and WECs.

Keywords: Breakwater; Wave energy converter; Hybrid system; Hydrodynamic performance; Power take-off.

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1. Introduction

With the depletion of the traditional energy resources and low carbon requirement, ocean renewable energy is attractive for its large reserves and exploitability in many sea areas (Clément et al., 2002; Wang et al., 2011; Lehmann et al., 2017; Guerra, 2018; Hemer et al., 2018; Neill et al., 2018). Even though the technical solutions of the wave energy utilization are mature to some extent and some devices are in the pre-commercial stage, the present research and developments indicate that wave energy devices are still far from reaching the stage of real engineering application (Cruz, 2007; Drew et al., 2009). The High construction cost of the WECs may directly lead to uneconomic price of the electricity converted from ocean wave power by WECs. Therefore, these high construction costs of WECs is one of the major obstacles that limits the past and future development of the wave energy utilization device (Ferro, 2006; Allan et al., 2011; Jeffrey et al., 2013; Astariz et al., 2015; Mustapa et al., 2017). The competitiveness of wave power extraction in the energy market can be enhanced by reducing the construction cost.

The cost-sharing strategy may be one of the solutions to reduce the construction cost. This can be achieved by combining two or more kinds of marine structures into one installation. It is worth noting that the marine structures to be combined would be producing the synergistic effect and operating in similar environmental conditions. Such similarities may pave the way for the integration of the different functional aspects. In addition, the multi-purpose objective of the marine structures can be achieved simultaneously.

The hybrid systems include breakwater-WEC integrations (Mustapa et al. 2017), offshore wind turbine-WEC integrations (Pérez-Collazo et al., 2015; Chen et al., 2016; Elginoz et al., 2017), offshore platform-WEC integrations (Zhang et al., 2017; Lee et al., 2018) and aquaculture cage-WEC integrations (Toner et al., 2002; Vassiliou et al., 2015; Lopes De Almeida, 2017). Examples of these integrations include: floating power plant P80 (Floating Power Plant Products & Services, 2019), Spar-Torus Combination (STC) concept (Muliawan et al., 2013), WindWaveFloat concept (Peiffer et al., 2011), Berkeley Wedge concept (Madhi et al., 2014), etc. Through the integration strategy, the cost-sharing, space-sharing and multi-functionality of the hybrid structures can be achieved. Consequently, the cost per structure can be effectively reduced and the engineering application of wave energy harvesting devices becomes more feasible.

WECs are used to convert wave energy to other useful forms. Theoretically, a capture width ratio (CWR) of 100% can be achieved by using a device with special design, such as a capturing buoy oscillating in multiple degree of freedoms (DOFs) (Evans, 1976) or an asymmetrical capturing buoy (Mynett et al., 1979). However, it is difficult to install a device with a CWR of 100% in the field conditions (Salter, 1974). When incident waves encounter a WEC array, part of the incident wave energy is absorbed and the remained unabsorbed part is transmitted across the WEC array. As a result, the wave height at the lee side of the WEC (array) is reduced significantly. The purpose of breakwaters is to attenuate wave energy and provide sheltering for coastal communities and infrastructure. The wave height at the leeside of breakwaters is smaller than that at the weather side. This is the common characteristic for the WECs (array) and breakwaters in terms of the wave transmission through wave barriers, which aids the argument for the integretated design of breakwater-WEC integrations. Besides, there are some investigations on the performance of WEC farms with the affiliated function of coastal protection (Abanades et al., 2015; Abanades et al., 2018).

Many design concepts of breakwater-WEC integrations have been proposed during the past several decades. In the earlier stages, the pilot breakwater-WEC integrated systems focused on the bottom-mounted breakwaters, such as caisson breakwaters (Takahashi, 1988), rubble-mound breakwaters (Margheritini et al., 2009; Vicinanza et al., 2014; Di Lauro et al., 2019), and composite sea walls (Buccino et al., 2015). Examples of the bottom-mounted breakwater-WEC integrated system include: the Sea Slot-cone Generator (SSG) device (Margheritini et al., 2009) and the Overtopping Breakwater for Energy Conversion (OBREC) device (Musa et al., 2017), etc. Mustapa et al. (2017) give a comprehensive review of the bottom-mounted hybrid breakwater-WEC system. By introducing those concepts, wave energy utilization in coastal areas becomes more attractive due to the sharing of the cost and space between the WECs and the breakwaters. It is known that the bottom-mounted breakwater becomes uneconomical in the relatively deep-water area. Floating breakwaters are favored for their lower construction cost and the added advantages of being flexible and environmentally-friendly (McCartney, 1985). Most of the floating breakwaters are of the form of floating surface-piercing structures. Similarly, some wave energy devices are often located at the free surface; for example, raft type devices, point absorbers and floating Oscillating Water Column (OWC) type devices. Besides the similarity in the configurations, the working environment conditions are similar for the WECs and the floating breakwaters. They are both employed in sea areas with abundant wave energy resources. The similarity in environmental conditions and structural configurations may provide the natural advantages for combining the floating breakwaters and WECs as hybrid systems.

In recent years, there has been a rapid development of floating breakwater-WEC integrations. Comprehensive reviews on floating breakwater-WEC integrations are absent in the literature. The objective of the present paper is to present a literature review on the research and development of different types of hybrid floating breakwater-WEC system. Furthermore, the technical issues and the challenges associated with these hybrid systems are discussed in a detailed manner. The advantages and disadvantages of different types of floating breakwater-WEC systems are also outlined in this review.

This paper is organized as follows. In Section 2, the classification of the floating breakwaters and WECs based on their working principles are introduced. Various approaches to integrate floating breakwaters with wave energy harvesting devices are classified and their characteristics, efficiency and survivability are reviewed in Section 3. The technology development issues and challenges of the hybrid system are discussed in Section 4. Finally, conclusions are drawn in Section 5.

2. Classifications of floating breakwaters and wave energy converters

2.1 Floating breakwaters

Floating breakwaters are favored for the advantageous reasons of relatively low construction costs, reduced dependencies on marine geological conditions, low environmental impact, aesthetic considerations and flexibility (McCartney, 1985). McCartney (1985), Sawaragi (1995) and Dai et al. (2018) presented comprehensive reviews of the research and development of floating breakwaters. According to the configurations, traditional floating breakwaters are categorized as follows: box-type, pontoon-type, frame-type, mat-type, tethered-floating type and horizontal-plate type. It is understood that the wave attenuation function of the floating breakwaters is achieved by dissipating incident wave energy or hindering the incident wave propagation. Hence, the wave attenuation principles of the floating breakwaters mainly include: reflecting type, disturbing type, and friction type (Sawaragi, 1995; Dai et al. 2018). Reflecting type breakwaters hinder the wave propagation by partially reflecting incident wave to the weather side of the breakwater, which leads directly to the reduction of wave height on the lee side of the structure. For the disturbing type breakwater, the original wave-particle orbit velocity can be disturbed by breakwaters with specific shapes and the resulting induced phenomenon of wave breaking or wave fission may dissipate the incident wave energy. Consequently, the aim of wave attenuation may be achieved. In contrast, the wave energy is dissipated by producing vortices caused by a particular media (such as tires) for the friction type breakwaters. The classification and wave attenuation principles of each type of floating breakwaters are shown in Table 1(Dai et al. 2018).

Table 1 Classification of the traditional floating breakwaters and the corresponding operational principles

Structural type	Wave attenuation principle
Box-type	Reflecting type
Pontoon-type	Reflecting type
Frame-type,	Disturbing type
Mat-type	Friction type
Tethered float type	Friction type
Horizontal plate type	Disturbing type

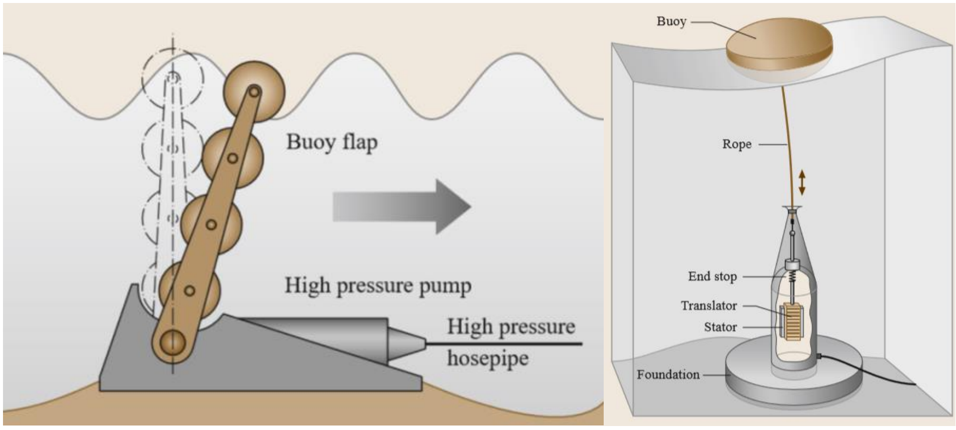
2.2 Wave energy converters

WECs are used to convert wave energy into a useful form (e.g., electricity). Based on the principle of capturing wave energy, WECs can be categorized as Oscillating Body (OB) type, OWC type, and overtopping type (Falnes, 2007; Drew et al., 2009; Falcão, 2010; Borthwick, 2016; Babarit, 2017). The sketches of each kind of WECs are shown in Figure 1-3.

For the OB type WECs, the movable bodies (floating or submerged) are selected as the "absorber" to capture wave energy. Wave energy is converted to kinetic energy of the body in the first step. Generally, the movable bodies are connected to the PTO system by a transmission mechanism (e.g., mooring line or rigid driving link). In this way, the body drives the PTO system directly and wave energy can be converted to electricity. Examples of the OB type WECs include Oyster (Renzi et al., 2014), PowerBuoy (Hart et al., 2012) and Seabased AB WEC (Chatzigiannakou et al., 2017), etc.

The OWC type WECs comprise a partially submerged structure with an opening below the water surface. Distinct components termed the air chamber and the water column are formed inside the structure (Falcão et al., 2016). The incident wave excites the motion of the water column, which may lead to the fluctuation of the air pressure in the chamber. The conversion of wave energy can be realized through an air turbine, which is driven by fluctuating air pressure. Examples of the OWC type WECs include LIMPET (Heath, 2000) and Mighty Whale (Hotta et al., 1996), etc.

Distinct from the above two devices, the overtopping type WECs involve a specific structure named a water reservoir. The overspilling of water waves fills the reservoir and, in this way, the wave kinetic energy is transformed into the potential energy of the stored water mass in the reservoir. The potential energy of the stored water can be converted to the electrical energy by using low-head hydraulic turbines. Examples of the overtopping type WECs include the Wave Dragon device (Kofoed et al., 2006) and the SSG device (Margheritini et al., 2009), etc.



(a) (b)

Figure 1 Sketch of the OB type WEC. a) Oscillating Wave Surge Convertors, Oyster device; b) point absorber, Uppsala Seabased AB device. Adapted from Xiros et al. (2016)

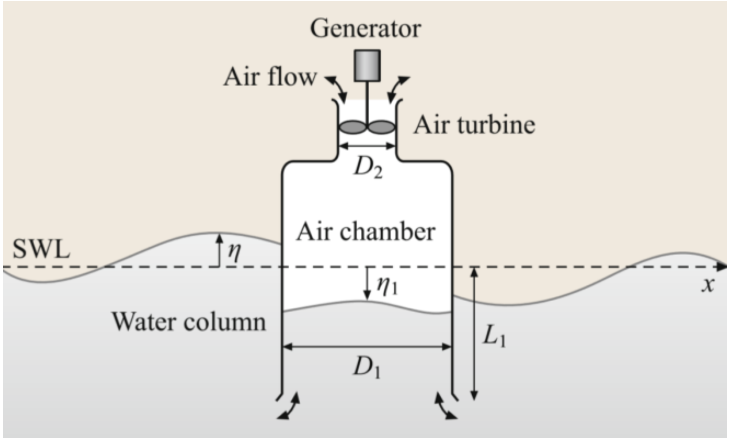


Figure 2 Sketch of the OWC type WEC. Adapted from Xiros and Dhanak (2016)

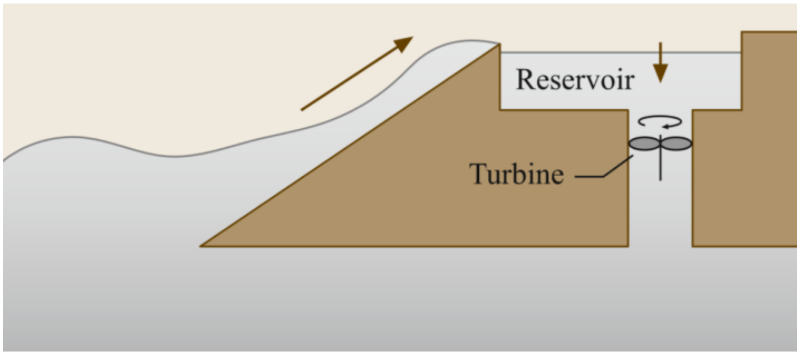


Figure 3 Sketch of the overtopping type WEC. Adapted from Xiros and Dhanak (2016)

3. Floating hybrid breakwater-WEC system

As described in Section 2, the working principles of conventional floating breakwaters include reflecting type, disturbing type, and friction type, etc. That is to say, the conventional floating breakwaters work by dissipating or reflecting the wave energy to achieve the aim of attenuating incident waves. In this way, part of the incident wave energy is transformed into the wasted energy. Coincidentally, WECs work on the principle of converting wave energy into other forms. The synergetic effect will be augmented if the floating breakwaters can be designed as wave-energy-utilizing type structures, in which the function of wave energy utilization and wave attenuation can be achieved simultaneously. In this section, we will present a comprehensive review of floating wave-energy-utilizing type breakwaters, i.e., hybrid floating breakwater-WEC systems. The hybrid systems are categorized as floating breakwater-OB type WEC systems, floating breakwater-OWC type WEC systems and floating breakwater-overtopping type WEC systems. In contrast to the conventional WECs or breakwaters, both conversion efficiency and transmission coefficients shall be examined while evaluating a hybrid system.

3.1 Floating breakwater-OB type WEC system

The floating breakwater-OB type WEC system combines the OB type WEC and the conventional floating breakwater. Generally, the breakwater acts as the base structure. Box-type breakwaters and pontoon-type breakwaters are common in this category. The hybrid system can be formed in 2 ways, i.e., 1) adding a PTO system on the original breakwater; 2) the additional attachment of a complete WEC (array) on the original breakwater. The main body of the breakwater is similar to that of the conventional floating breakwater (retaining its pontoon shape or box shape).

Box type breakwaters are attractive for their advantages of durability, simplicity and easy-to-construct, etc. Some floating box-type breakwaters have reached the stage of engineering application (Kusaka et al., 2015; Com, 2017). Due to the simplicity and ease of modification, Pile-restrained Floating Breakwaters (PRFBs) are often adapted to form a hybrid system with the dual functions of coastal protection and wave energy utilization. Previous investigations verified that such kind of breakwater operates effectively in terms of the wave attenuation performance (Isaacson et al., 1998; Koutandos et al., 2004; Koutandos et al., 2005; Diamantoulaki et al., 2008; Wang et al., 2010).

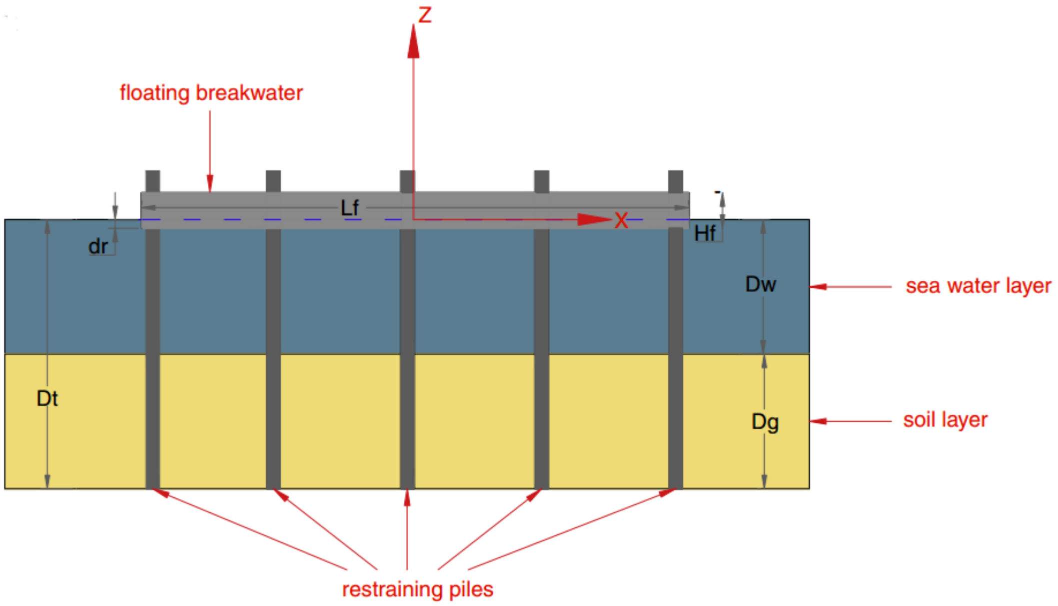


Figure 4 Section view of the pile-restrained floating breakwater. The rectangular breakwater moves in heave mode under the restriction of the vertical piles. Adapted from Diamantoulaki et al. (2008)

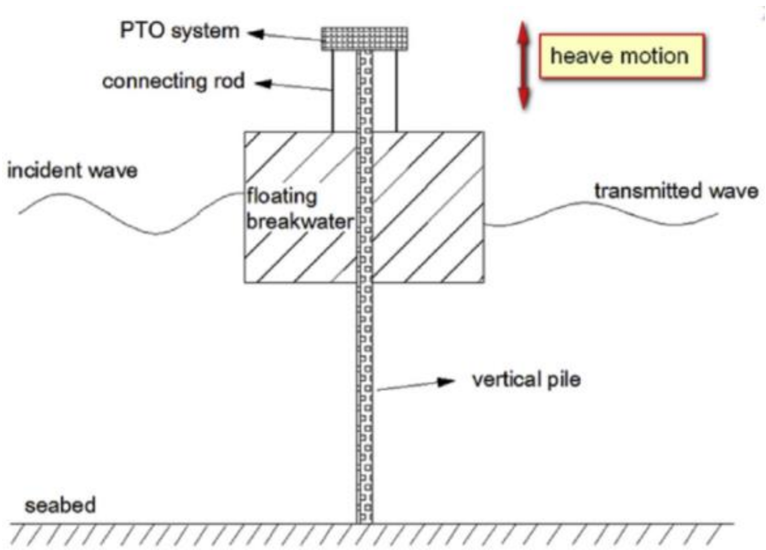


Figure 5 Sketch of the hybrid system. The pile-restrained floating pontoon moves in heave mode and a PTO system driven by the floating pontoon achieves the wave power absorption. Adapted from Ning et al. (2016)

The floating pontoon of the PRFB moves in heave mode under the restriction of the vertical pile (as is shown in Figure 4). Similarly, the energy-capturing body of the heaving OB type

WEC moves in heave mode (Zang et al., 2018). The similarity in motion characteristics may pave a way to integrate the two aspects as one. Ning et al. (2016) proposed a hybrid system (as shown in Figure 5) by matching a PTO system to the PRFB. Similar to the conventional PRFB (Koutandos et al., 2004; Diamantoulaki et al., 2008), the shape of the floating body remaines as a rectangular box. Zhao et al. (2017) investigated the performance of such kind of hybrid system based on linear potential flow theory. The condition of CWR η > 20% and transmission coefficient $K_T < 0.5$ can be achieved at a certain frequency range. A corresponding experimental investigation was conducted by considering the nonlinearity of the PTO damping force (Ning et al. 2016). Experimental results reveal that the qualified CWR and the effective wave attenuation performance can be achieved simultaneously. The disadvantage of this hybrid system is the poor wave attenuation performance when the device is operational in long waves. This shortcoming results from the box type breakwater. The PTO system slightly modifies the transmission coefficient of the hybrid system in long waves. In addition, the theoretical maximum value of the CWR for the heaving two-dimensional pontoon (moving in single mode) is 50%. Due to the fluid viscous effect and friction losses, the optimal CWR is smaller than 50% in the laboratory test. Consequently, the frequency range satisfying the condition of η > 20% and $K_T < 0.5$ (hereinafter called effective frequency range) is narrow.

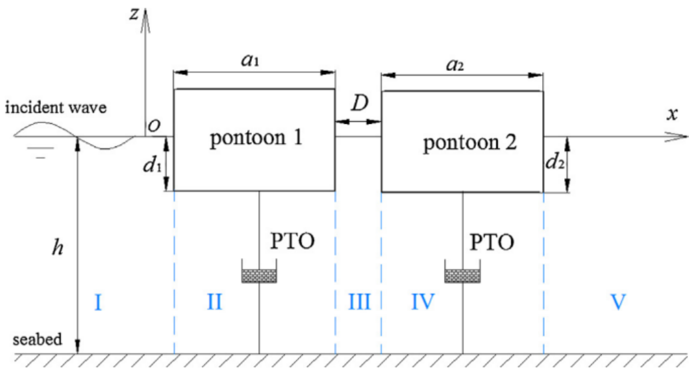


Figure 6 Sketch of the dual pontoon-PTO system. The two pontoons and their matching the PTO system (arranged in tandem) work independently. Adapted from Ning et al. (2017)

Comparing with the single pontoon system, the dual pontoon type breakwater gives better breakwater performance (Koutandos et al., 2005). The energy conversion performance of WECs consisting of several small buoys is shown to be better than that of a single buoy system with equal total volume (Garnaud et al., 2009). To broaden the effective frequency range of the breakwater-WEC system proposed in Ning et al. (2016), Ning et al. (2017) put forward a dual pontoon-PTO system consisting of two pontoons and two PTOs as shown in Figure 6. Preliminary analytical investigation revealed that the effective frequency bandwidth (i.e., the width of the effective frequency range) of the dual pontoon-PTO system is broader than that of the single pontoon system with equal total pontoon volume. The efficiency of the former case is obviously greater than that of the latter one (Ning et al., 2017). Even though the friction losses and viscous effect play an important role in experiments, conclusions obtained from experimental research data verifies the advantages of the dual pontoon, dual PTO system (Ning et al., 2018). Note that two PTO systems are needed for the dual pontoon-PTO system, and only one PTO system is needed for the single pontoon system. This may lead to the increase of installation cost.

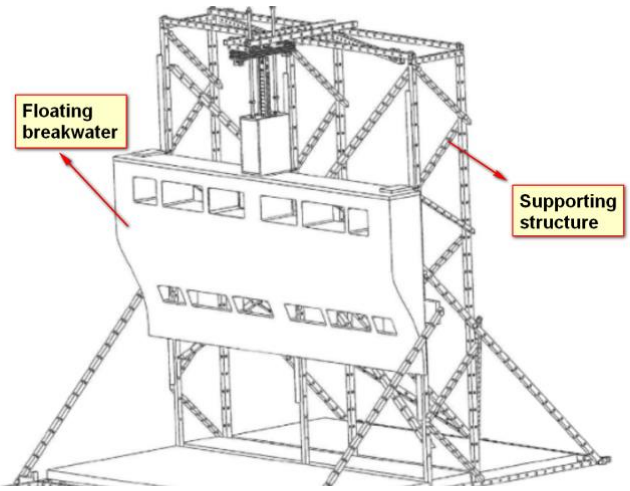


Figure 7 Sketch of the TBW. The working principle of this system is similar to that of the system described in Fig. 5. The floating buoy is designed as a wedge-shaped structure. Adapted from Madhi et al. (2018)

Madhi et al. (2015) proposed a concept called ‘The Berkeley Wedge’ (TBW), which consists of a floating wedge-shaped box and a PTO system installed above the floating body as shown in Figure 7. The floating body moves in heave mode and drives the PTO system to produce power. The shape of the floating body described in Madhi et al. (2015) is different from that in Ning et al. (2016). Specifically, the floating wedge-shaped box is designed such that the draft of the rear wall is larger than that of the front wall. This asymmetrical characteristic is similar to the Salter Duck device (Salter, 1974; Wu et al., 2018). Comparing the TBW with the conventional symmetrical device, the devices with the asymmetrical wedge-shaped body is beneficial to the improvement of the energy conversion efficiency (Madhi et al., 2014). This is due to the fact that the radiated waves at the leeside of the device are very small. Similar mechanisms can also be used to illustrate the high efficiency of the Salter Duck device (Mei, 1976; Evans, 1976). Consequently, the transmitted wave energy at the lee side of the breakwater will be reduced effectively (Madhi et al., 2014). This suggests that the effective coastal protection function can be realized if it acts as a breakwater. However, for the pontoon-type breakwater, a tough challenge is to make the transmission coefficient acceptable in longer waves.

To further improve the competitiveness of the TBW, some investigations were conducted from the point view of safety and survivability in both operational and extreme conditions (Tom et al., 2017; Madhi and Yeung, 2018). Tom et al. (2017) proposed a power-to-load balancing strategy to maximize power capture while minimizing structural and actuator loads. The survivability of the Berkeley wedge device in extreme waves was examined using Computational Fluid Dynamics (CFD) method (Madhi and Yeung, 2018). The modification of a pressure-relief channel (PRC) is introduced to improve the survivability of the device (Madhi and Yeung, 2018). The PRC design can be realized by removing part of the device that may experience the large wave pressures due to the slamming phenomenon.

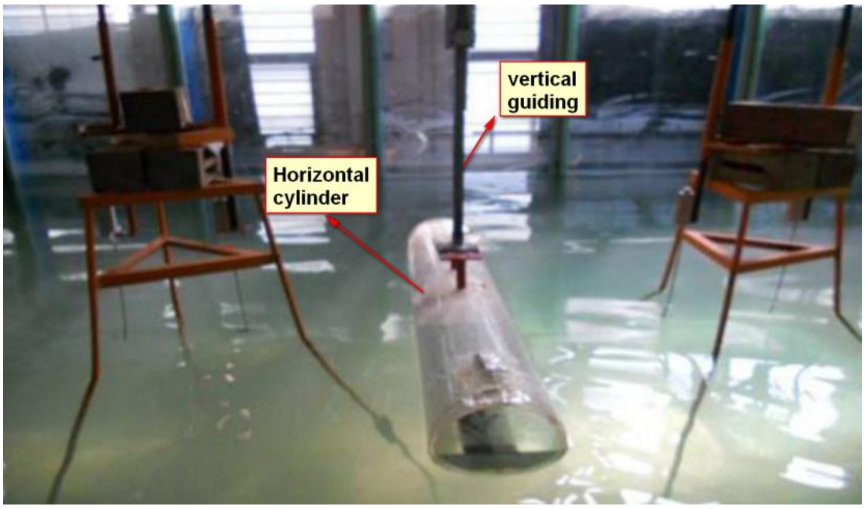


Figure 8 Wave flume test of the cylindrical device. The energy capturing bouy (i.e., the cylinder) moves in heave mode and is configuraged horizontally. Adapted from Chen et al. (2016).

Chen et al. (2015) proposed a wave energy system consisting of several floating horizontal cylinders. Each cylinder moves in heave mode and works independently as shown in Figure 8. The size of the cylinders is obviously smaller than that of the floating body in Ning et al. (2016) and Madhi and Yeung (2018). Chen et al. (2016) thoroughly investigated the performance of the system proposed in Chen et al. (2015) using a numerical wave flume technique. The wave attenuation performance of a single device in Chen et al. (2015) is not comparable to that in Ning et al., (2016) and Madhi and Yeung (2018). They pointed out that the qualified energy conversion performance and breakwater performance can be anticipated by deploying multiple devices.

Waves formed at the front of the breakwater are characterized as the superposition of the incident waves and the reflected waves, which may amplify the wave height at the weather side. This characteristic may be useful to improve the efficiency of WECs. There have been many attempts to combine WECs and floating breakwaters by attaching WECs at the weather side of the breakwaters (Zingale, 2002; Martinelli et al., 2016; Favaretto et al., 2017; Zhao et al., 2017; Ning et al., 2018; Zhao et al., 2019). Zingale (2002) proposed a modular floating breakwater with the additional function of wave energy utilization. As shown in Figure 9, an array of spherical OB type WECs were arranged at the weather side of the floating breakwater. The PTO system was arranged at the top of the breakwater, which acted as the base structure. As described in Figure 9, the size of the breakwater is obviously greater than that of many wave energy devices. The relative motion of the WEC devices and the breakwater drives the PTO system to produce power. Specific data on the efficiency and transmission coefficient of the integrated system are absent from the published results.

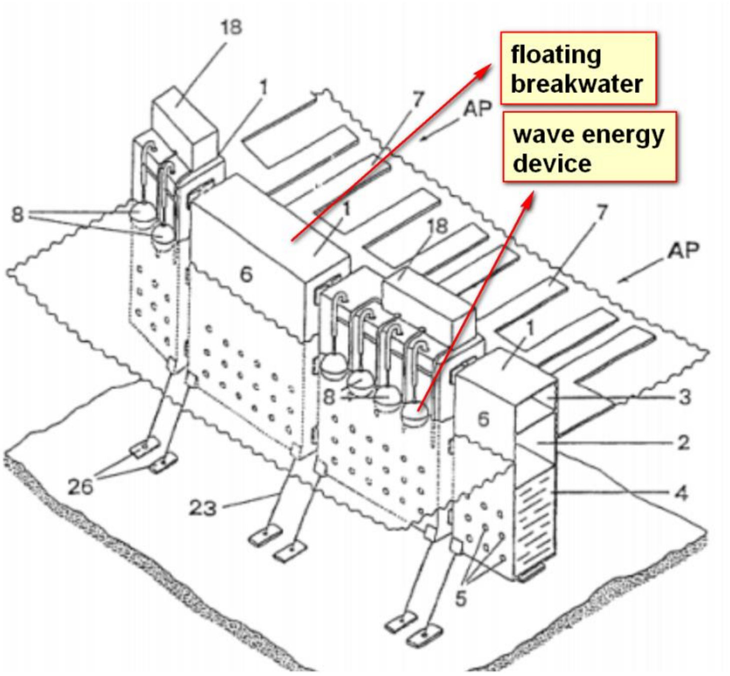


Figure 9 Sketch of modular floating breakwater-WEC system. Several oscillating buoy type wave energy devices were arranged at the weather side of the moored floating breakwater. Adapted from Zingale (2002)

Zhao et al. (2017) proposed a hybrid system comprising of an OB type WEC arranged in front of a floating pontoon-type breakwater. The efficiency of the OB type WEC arranged in front of the breakwater is greater than that of the isolated case in a wide frequency range. The superposition of the incident waves and reflected waves amplify the efficiency of the WECs. The corresponding experimental results revealed that the efficiency of the OB type WEC arranged in front of the breakwater is obviously greater than that of the isolated case, especially for shorter waves (Zhao et al., 2018). As a general extension, Ning et al. (2018) investigated the effect of the breakwater on the performance of a WEC array located at the weather side. A significant increment in the efficiency of the WEC array can be observed due to the existence of the rear breakwater. Corresponding experimental results show that the wave forces and heave response of the WECs can be amplified (Zhao et al., 2019). Such kind of integrations with significant improvement of the efficiency may pave the way to improve the energy conversion performance of WECs in areas experiencing medium wave conditions. It is important to note that zero efficiency occurs at certain frequencies for the devices located at the weather side of a breakwater. This is due to the fact that Bragg resonance with strong reflections may be triggered for such kind of multi-body system (Ouyang et al., 2015). When Bragg resonance occurs, wave forces acting on the front buoy are almost negligible. This may directly lead to the zero efficiency of the device. Due to the constructive effect on the energy conversion efficiency, Bragg resonance should be avoided while designing the integrations characterized by the multi-body system.

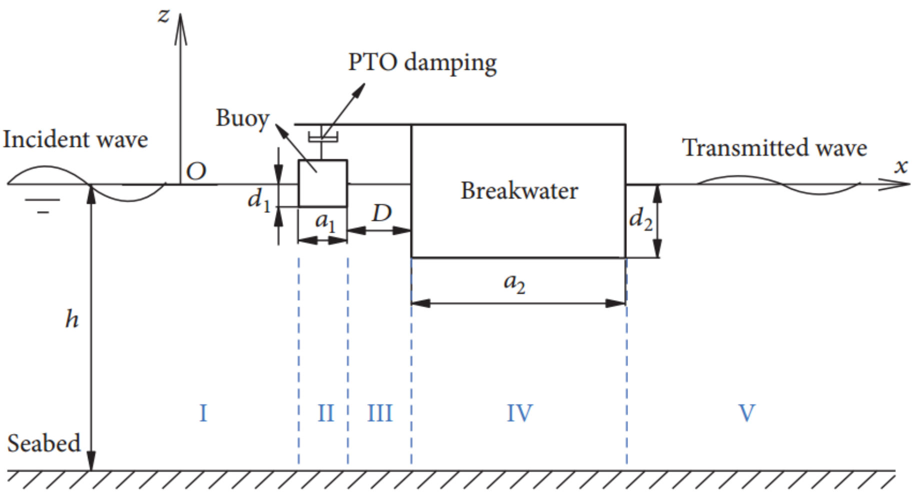


Figure 10 Sketch of the floating breakwater-WEC system. One PTO system is used to link the front buoy and the floating breakwater in fixed type configuration. Adapted from Zhao et al. (2017)

Martinelli et al., (2016) proposed a multi-functional structure combining a breakwater and an OB type WEC (namely ShoWED). The breakwater moves vertically along an upright pile as shown in Figure 11. ShoWED is situated at the weather side of the breakwater. Experimental results reveal that the energy conversion efficiency can reach 26%. This efficiency of 26% is smaller than that presented in Zhao and Ning (2018). Since the two contrasting configurations in

Martinelli et al. (2016) and Zhao and Ning (2018) are not the same, the direct comparison of efficiencies between the two systems is inapplicable. The relatively low efficiency indicated that further optimization of the system proposed by Martinelli et al. (2016) may be necessary to improve its energy conversion efficiency. As an extension, Favaretto et al. (2017) proposed a novel integrated system consisting of a catamaran floating breakwater and an OB type WEC. The aim of generating electrical energy whilst also providing a coastal protection function can be achieved for both of the systems proposed in Refs. (Martinelli et al., 2016; Favaretto et al., 2017).

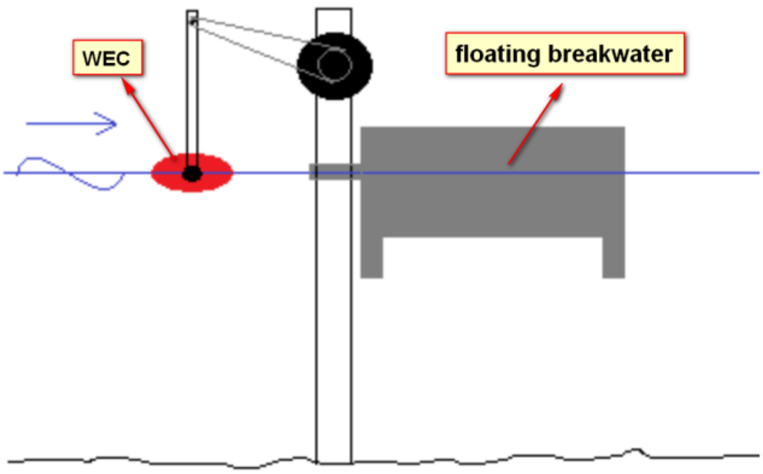


Figure 11 Sketch of the hybrid floating breakwater-WEC system proposed by Martinelli et al. (2016). A WEC (ShoWED) was attached at the weather side of the breakwater, which moves in heave mode along the vertical pile. Adapted from Martinelli et al. (2016).

For the above mechanisms described in this subsection, the energy capture body of the device moves in heave mode. In contrast, the devices described below belong to the category of multi-mode WEC. The energy-capturing body moves in multiple degrees of freedom. Michailides et al. (2011) proposed a flexible floating breakwater consisting of several modules as shown in Figure 12. The neighboring modules are connected by the PTO system, which is driven by the relative motion of the modules. This is similar to the raft-type WEC, as mentioned in Zheng et al. (2017). The energy conversion performance and wave attenuation performance of such a system were investigated theoretically (Michailides and Angelides, 2012; Michailides et al., 2013; Michailides et al., 2015; Michailides, 2017). Results revealed that the system can simultaneously satisfy the effective energy conversion efficiency and qualified wave attenuation performance. So far, there are no corresponding experimental investigations reported. The flexible floating breakwater can be fixed by a mooring system and deployed in the deep-water area. Comparatively, it is uneconomic to deploy the pile-supported system in deep water. A sea location with medium depth may be favorable for the pile-supported system.

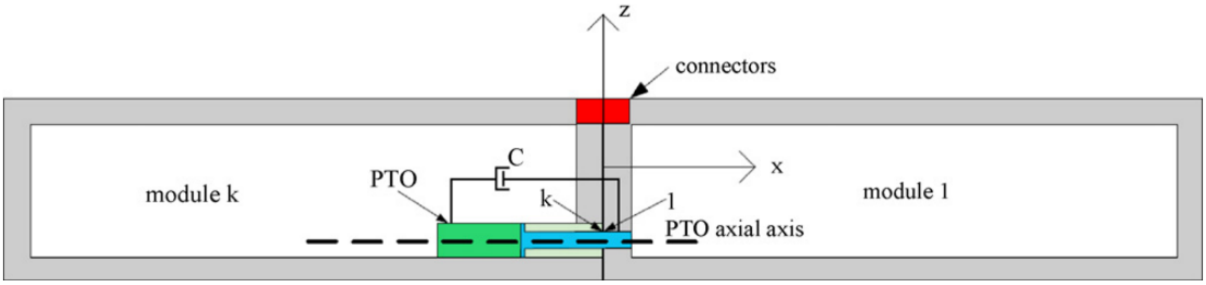


Figure 12 Sketch of the multiple module flexible floating breakwater-WEC system proposed by Michailides and Angelides (2011). The two neighboring modules were connected by the PTO system. Adapted from Michailides and Angelides (2011)

3.2 Floating breakwater-OWC type WEC system

The floating OWC type device is a hollow-shaped structure (Luo et al., 2014; Elhanafi et al., 2017). The hollow-shaped structure can be formed by removing the bottom of the conventional floating box/pontoon type breakwater. Generally, the displacement of the OWC type breakwater is smaller than that of the OB type breakwater. This may result in a relatively lower construction cost of the OWC type breakwater. Neelamani et al. (2006) proposed a floating OWC caisson structure with an air chamber as shown in Figure 13. The anchor chain mooring system is adapted to fix the system in location. From the experimental data on the pneumatic efficiency of the system, it can be deduced that the system can be effectively used as breakwaters and as WECs. Koo (2009) investigated the wave attenuation performance of a pneumatic-type floating breakwater as shown in Figure 14; this structure possesses the characteristics of the OWC type wave energy device. The imposed pneumatic damping is helpful to dissipate wave energy and improve the wave attenuation performance. Hence, the wave attenuation performance of the pneumatic-type floating breakwater is better than that of the conventional box type breakwater.

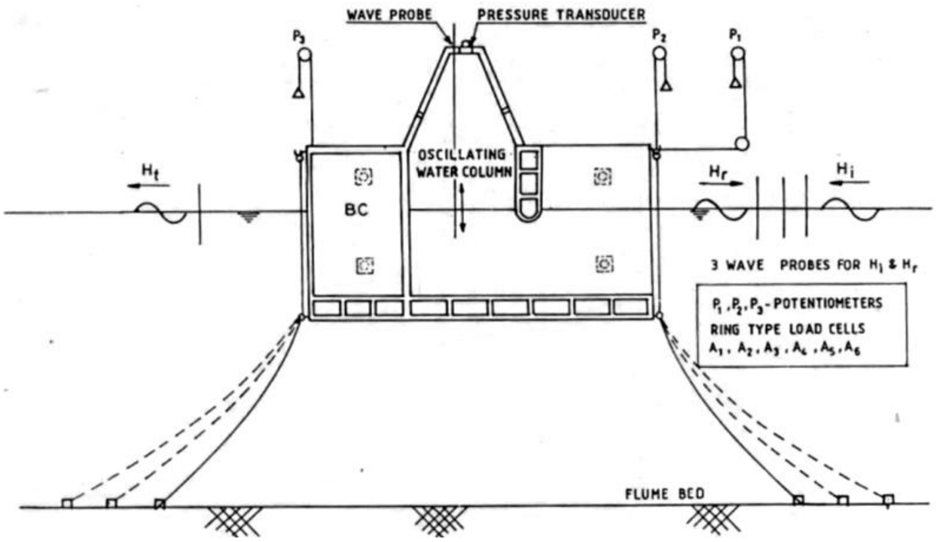


Figure 13 Sketch of the floating OWC type breakwater. The moored breakwater is a hollow type structure. In the middle section of the breakwater, an OWC and an associated air chamber are formed. Adapted from Neelamani et al. (2006).

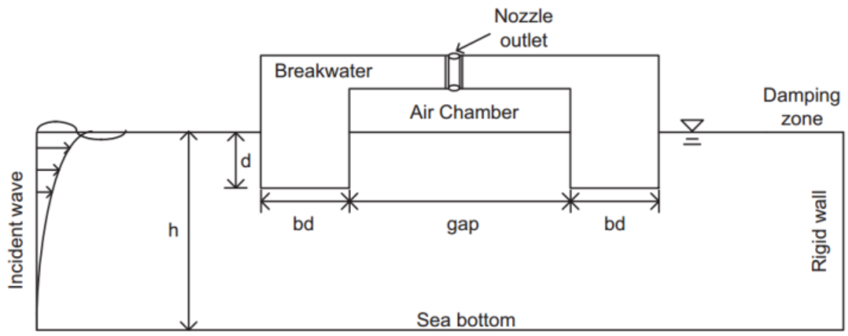


Figure 14 Sketch of the pneumatic-type floating breakwater. The breakwater with finite-thickness wall and a nozzle outlet is arranged above the air chamber to provide damping effect. Adapted from Koo (2009)

He and Huang (2014) proposed a pile-based breakwater with an OWC air chamber. In appearance, the new breakwater design is equivalent to a bottomless box. Compared with the conventional pile-supported box-type breakwater, the wave attenuation performance of the device is improved due to the energy absorption function of the air chamber. Furthermore, the measured fluctuations in air pressure revealed that this kind of device is suitable for wave energy utilization. He et al. (2012) proposed a breakwater with double OWC air chambers. The two OWC air chambers are symmetrically located at the front and rear sides of the box. Additionally, this system has the potential to harvest wave energy. He et al. (2013) and He et al. (2017) modified the hybrid system proposed in He et al. (2012) by incorporating two asymmetric air chambers. As a result of the modifications, the pressure fluctuation inside the air chamber (arranged asymmetrically) are amplified significantly. This is beneficial to improve the wave energy conversion efficiency without compromising the coastal protection function.

Through integrating the air chamber into the conventional breakwater, the function of wave energy conversion can be achieved. More importantly, compared with the conventional box-type breakwater, the wave attenuation performance of the hybrid system is improved. This is attributed to the fact that wave energy is dissipated by pneumatic damping, which can be observed directly from the fluctuation of the air pressure in the chamber. In addition, the embedding of the OWC air chamber decreases the displacement of the breakwater. For floating bodies, the displacement roughly indicates the construction cost. So the reduction of the construction cost may be achieved adjunctively.

Sundar et al. (2010) proposed a novel floating breakwater–OWC WEC system as shown in Figure 15. The system combines the U-OWC device and the floating box-type breakwater. Many theoretical and experimental investigations verified that the U-OWC is an effective land-based OWC device (Boccotti, 2007; Strati et al., 2016; Malara et al., 2017). So far, both the theoretical and experimental investigations that evaluate the performance of this novel floating system are absent.

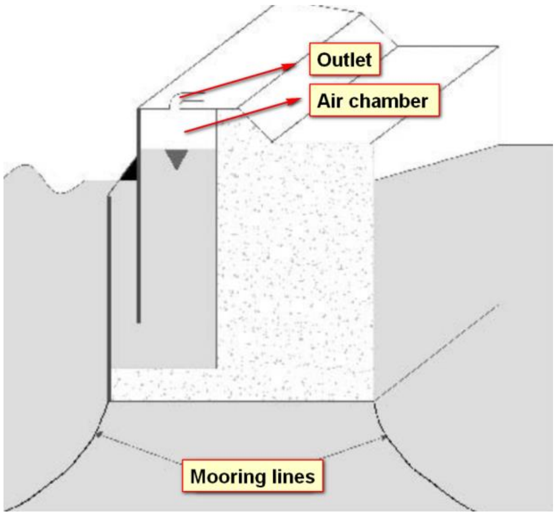


Figure 15 Sketch of the floating skirt breakwater with OWC. Contrary to the conventional OWC devices, the front submerged wall is included to form the U-OWC concept. Adapted from Sundar et al. (2010)

Since the OWC WEC has the preliminary function of absorbing wave energy; it can serve as a sheltering structure for particular offshore engineering installations. Hong and Hong (2007) and Hong et al. (2006) applied the concept of using floating OWC breakwaters to shelter the Very Large Floating Structures (VLFS) by arranging the WECs at the weather side of the VLFS. Since part of the incident wave energy is absorbed by the OWC breakwater, the response of the VLFS can be reduced effectively.

3.3 Floating breakwater-overtopping type WEC system

MSc Erik Friis-Madsen proposed an overtopping type WEC called Wave Dragon, which can also serve as a wave-damping structure (Kofoed et al., 2006). Unlike conventional WECs, this device includes two reflection walls as shown in Figure 16, which can amplify the wave height substantially. This typical design is beneficial to improve the wave energy conversion efficiency of the wave energy harvesting device. The main structure of the Wave Dragon device consists of a curved ramp and a water storage reservoir. Incident waves can be focused by the reflectors and the overtopping water fills the reservoir. The potential energy of the water in the reservoir is converted into electricity through low-head hydro turbines. Small-scale laboratory test and offshore test with the scale of 1:4.5 showed that the device operates effectively in terms of the PTO performance (Soerensen et al., 2000; Hansen et al., 2003; Frigaard et al., 2006). Beels et al. (2010) investigated the influence of the existence of the Wave Dragon device on the surrounding wave field. Due to its excellent wave absorbing performance, the Wave Dragon device has the potential to act as a breakwater (Nørgaard et al., 2013).

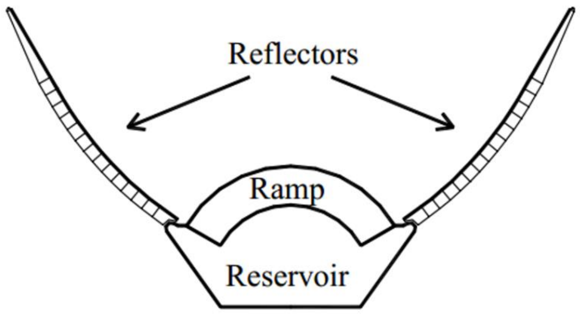


Figure 16 Sketch of the of the Wave Dragon device. Wave height was amplified due to the wave gathering effect produced by the two reflectors. This resulted in the reservoir filling with the overtopping water. Adapted from Kofoed et al., (2006)

3.4 WEC array with sheltering function

The essential purpose of a wave farm (i.e., WEC array) is to transform wave energy into other useful forms. This means that the incident wave energy will be partially absorbed while the waves transmitted through the WEC array and, consequently, the wave height at the lee side of the WEC array is mitigated (Carballo et al., 2013; McNatt et al., 2015; Flocard et al., 2017; Abanades and Flor-Blanco et al., 2018; Rodriguez-Delgado et al., 2018). Naturally, the wave farm may possess the function of sheltering or providing coastal protection from erosion.

The conventional coastal protection structures are single-functional and no other benefits can be achieved. Many attempts have been made to realize multiple functionality (including wave energy utilization, wave attenuation, etc.). Wave farms with a coastal protection feature are preferable for their advantageous multiple function, cost-sharing and space-sharing. McNatt et al. (2015) presents the wave fields as shown in Figure 17 around a WEC array consisting of several point absorbers (situated by using an analytical method based on linear potential theory). It can be directly observed that wave height at the lee side of the WEC array is obviously smaller than that at the weather side. This may provide intuitive evidence that a WEC farm can act as a single synergistic structure with effective wave attenuation performance.

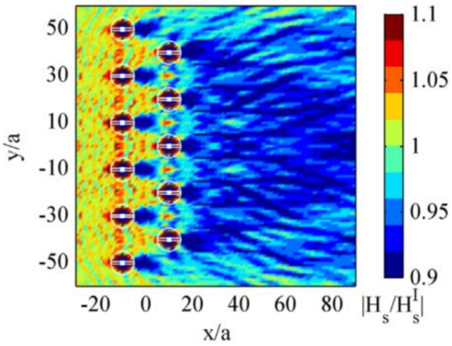


Figure 17 Wave field around the WEC array. H_S and H_S^I denotes significant wave height and the incident significant wave height, respectively. For the detailed information of the WEC array see McNatt et al. (2015). Adapted from McNatt et al. (2015).

Zanuttigh et al. (2010) analyzed the breakwater performance and energy conversion efficiency of a floating WEC (i.e., DEXA). The DEXA device is essentially formed by two hinged floating buoys, and the relative motion of the hinged buoys drives the PTO system. Using the DEXA device, energy conversion efficiency of 10%~35% can be achieved in laboratory conditions. The transmission coefficient for the single device and double devices with staggered configuration are 0.8 and 0.6, respectively (Zanuttigh et al., 2013). From this trend, it can be deduced that more effective wave attenuation performance can be obtained for a WEC array with many DEXA devices.

Since a reduction in wave height is observed behind a wave farm, it can be used to protect coastal areas from erosion. The role of the wave farm from a perspective of providing coastal protection from erosion is analyzed in Refs. (Bergillos et al., 2018; Abanades et al., 2014; Abanades et al., 2015). As is expected, the wave farm induces a wave height reduction at its lee side and significant reduction in erosion of the beach can be achieved. It is worth noting that the distance between the coast and the wave farm affects the shelter pattern (Abanades et al., 2015). Mendoza et al. (2014) investigated the beach response to wave farms (consisting of classical WECs, such as DEXA, Wave Dragon, SeaBreath, Blow-Jet, etc.) acting as a coastal defense.

They pointed out that the farm layout with several lines of WECs is favorable for near-shore protection purpose. Nevertheless, the other coastal activities (such as aquaculture, navigations, etc.) should be taken into account while designing such kinds of wave farm with the function of coastal protection.

Sheltering effect is an important function of a wave farm. In addition to the function of coastal protection from erosion, wave farm can provide sheltering for other marine operations, such as offshore wind farm, aquaculture facilities, etc. (Weiss et al., 2018). Many hybrid wave-wind farm schemes have been proposed (Astariz et al., 2015; Pérez-Collazo et al., 2015). Due to the sheltering effect of the wave farm, wave conditions at the proposed areas will be more moderate (Veigas et al., 2014; Astariz et al., 2015; Astariz et al., 2015; Onea et al., 2016). Hence, longer design life periods and lower maintenance costs for the offshore wind turbines can be realized. Similarly, offshore renewable energy devices can also provide power for the offshore aquaculture facilities and stimulate the synergies between the two aspects. This may provide opportunities for co-location of offshore renewable energy devices and aquaculture farms. Making full use of the function of sheltering and power supply features of WECs may enhance the competitiveness of the ocean wave energy resource.

4. Issues and challenges

The floating breakwater-WEC hybrid systems possess dual functions (i.e., breakwater function and wave energy utilization). The performance indexes of the hybrid systems are different from that of original breakwaters or WECs with single function. For the conventional structures, only one indicator (transmission coefficient or wave energy conversion efficiency) may be of concern. However, for the hybrid systems, both the functions of wave energy conversion and coastal protection shall be considered collectively. Hence, the design methods or the test procedures for the conventional breakwaters or WECs may not suitable for the hybrid systems.

Table 2 Comparisons of the achievable transmission coefficient and efficiency of some hybrid systems. A, B and C represent the floating breakwater-OB type WEC system, floating breakwater-OWC type-WEC system and WEC array with sheltering function, respectively. W2W denotes wave-to-wire.

Hybrid system	Transmission coefficient	Efficiency	Efficiency measurement	Category	Reference
Single pontoon system	0.4-0.55	0-35%	W2W measured value	A	(Ning et al., 2016)
Dual pontoon-single PTO system	0.42-0.55	42%-55%	W2W measured value	A	(Zhao and Ning, 2018)
Dual pontoon- PTO system	0.34-0.52	22%-51%	W2W measured value	A	(Ning et al., 2018)
The Berkeley Wedge	0.125	96%	Theoretical value	A	(Madhi et al., 2018)
Double horizontal cylinder	0.71-0.85	25%-42%	W2W numerical value	A	(Chen et al., 2016)
Floating breakwater-WEC system	0.5	20%	W2W measured value	A	(Martinelli et al., 2016)
Catamaran breakwater-WEC system	< 0.5	37% (resonant condition)	W2W measured value	A	(Favaretto et al., 2017)
Floating wave energy caisson breakwaters	< 0.5	50% (maximum efficiency)	Experimental pneumatic efficiency	B	(Neelamani et al., 2006)
Floating breakwater with dual pneumatic chambers	-	44% (maximum efficiency)	Experimental pneumatic efficiency	B	(He et al., 2017)
DEXA device	0.8 for single device,	10%-35%	W2W measured value	C	(Zanuttigh et al., 2013)

	0.6 for double device	

For the hybrid breakwater-WEC systems, the ideal condition is that the incident wave energy is totally absorbed by the WECs and the scattered wave energy is canceled at a wide frequency range. Previous theoretical investigations reveal that an efficiency of 100% can be achieved for devices with multiple DOFs (Evans, 1976). However, it is challenging to achieve this ideal condition in reality. It is understood that the transmission coefficient is an important indicator while evaluating the wave attenuation performance of the floating breakwater. For a specific floating breakwater that meets the engineering application design, the transmission coefficient should be maintained below 0.5. Hence, under the premise of $K_T < 0.5$, hybrid systems with higher energy conversion efficiency are more competitive. Table 2 showed the achievable transmission coefficient and efficiency of some selected hybrid systems. It can be observed that the hybrid systems with OB type WECs perform better in terms of the wave energy conversion efficiency. Improvement of the energy conversion performance of the WECs can be achieved by two methods: 1) making full use of the waves reflected from the adjacent structures; 2) optimizing the energy-capturing buoy performance through methods such as the use of asymmetrical bodies (such as the TBW). In addition, the effective frequency bandwidth (with effective efficiency and a qualified transmission coefficient) is another important indicator that evaluates the performance of the hybrid system. Hybrid systems with broader effective frequency bandwidths are favorable.

For most of the floating breakwaters, poor wave attenuation performance in long wave conditions may lower their competitiveness. For hybrid systems that possess the characteristics of floating breakwater, similar issues still exist. Generally, floating breakwaters work effectively in short waves. However, wave energy devices operate ineffectively with features of low efficiency. High efficiency for WEC system in short waves is very important for the applications in the sea areas with mild wave conditions, such as the East China Sea (Wang et al., 2011). Hence, improving the energy conversion efficiency in short waves and the wave attenuation performance in long waves is necessary to broaden the effective frequency bandwidth of the floating hybrid systems.

Most of the existing investigations were conducted in long-crested wave conditions. However, real ocean waves are multidirectional and coexist with wave-currents. There are some investigations that evaluate the performance of the conventional WECs in multi-directional waves, such as (Göteman et al., 2018). However, considering the hybrid systems, the data indicating the performance of the integrated system in short-crested waves and coexisting wave-current fields is rare and there is a necessity for further investigations.

The survivability of the hybrid system in extreme waves determines its prospects in engineering applications (Tiron et al., 2015; Saincher et al., 2016). The occurrence of extreme wave events accompanies the interaction of breaking waves and structures. These are a complex phenomenon characterized by flow separation and air-entrainment (Saincher and Banerjee, 2016; Wei et al., 2016; Chen et al., 2018; Martin-Medina et al., 2018). Fundamentally, developing corresponding efficient numerical techniques (such as the CFD method) and high-quality experimental procedures may pave the way to understand this complex hydrodynamic problem (Saincher and Banerjee, 2016; Windt et al., 2018). Further exploring the mechanics of the hydrodynamic behavior of floating buoys in breaking waves and proposing advanced protection strategies are necessary to improve the survivability of the hybrid system.

So far, most of the concepts are in the stage of theoretical study or small-scale laboratory test. As a design stage that must be completed, large-scale experiments and sea trial tests with the implementation of the real hydraulic PTO systems are urged.

5. Conclusions

In this paper, a literature review was presented with a focus on the research and development of various types of hybrid floating breakwater-WEC systems over the past few years. The features and the advantages and disadvantages of different types of floating integrations were described. The corresponding challenges and issues were specified from the point view of fundamental hydrodynamics and technical solutions.

The conventional floating breakwaters and conventional wave energy devices are introduced and categorized based on their working principles. As hybrid structures with dual functionality (wave energy utilization and wave attenuation), the floating breakwater-WEC systems are categorized as the wave-energy-utilizing type breakwater. The floating breakwater-WEC systems are divided into four categories: floating breakwater-OB type WEC system, floating breakwater-OWC type WEC system, floating breakwater-overtopping type WEC system, and floating WEC array with sheltering function. Since such kind of systems were characterized by the cost-sharing, space-sharing and their multiple capabilities, the concept of combining the two aspects of protection and energy generation is beneficial to reduce the construction cost of both floating breakwaters and WECs. In addition, we present some investigations on wave farms with the dual function of coastal protection from erosion and sheltering specific engineering installations (such as offshore wind farms).

The floating breakwaters-WEC system is an attractive solution to coastal engineering, island engineering, aquaculture engineering and other massive ocean engineering projects (e.g., VLFS) that need power supply and protection against wave action. Even though many effective concepts have been proposed, there remain many untapped research areas. The main interesting outstanding challenges include evaluating the performance of the hybrid system in realistic sea states (i.e., multi-directional waves, wave-current coexisting filed, etc.), broadening the effective frequency bandwidth of the hybrid system, examining survivability of the hybrid system in extreme waves, etc. Since the marine structures must survive severe storms, the new challenges for the hybrid system are how to improve the survivability of the devices and propose further design guidance.

Further studies may also include the fundamental research on wave-structure interactions (especially for breaking wave-structure interactions) and protection strategies from extreme sea states to improve the survivability of these installations. Of course, novel designs of the hybrid system with simplicity in configuration, high energy conversion efficiency, excellent wave attenuation performance and broad effective frequency bandwidth are welcomed.

Acknowledgments

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